A SIMPLE CORRELATION FOR POLLUTION DISPERSION PREDICTION IN URBAN AREAS

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This draft note summarises the work undertaken in the design of the first DAPPLE tracer experiment. It is presented here as it may be of wider interest. Any comments or questions could be dircted to the authors.

1. Introduction

The dispersion of pollutants in an urban environment is largely determined by the pollutant emissions, the urban meteorology and the urban topography. The stochastic nature, of atmospheric dispersion is a dominant feature of the process, and this introduces limitations for deterministic mathematical predictions. Consequently there are many levels of mathematical modelling approaches, each appropriate for particular tasks. It has been found useful in the past to try to develop very simple models in order to scope out a problem prior to more detailed investigation. Frequently such very simple models are, nonetheles, directly useful in air quality studies and management. Scientific and statistical evaluation of the predictive models ensures an acceptable quality and can enhance confidence in the predictions.

In designing the first field tracer release experiment in DAPPLE it was necessary to estimate the link between the source release rate and the receptor concentrations (source-receptor relationship). Knowledge of this relationship allowed for correct receptor design and determination of optimum source release rates. Two approaches were used. Wind tunnel modelling was undertaken for various source and receptor positions. Additionally and prior to any field or wind tunnel measurements some simple mathematical modelling was attempted. This essentially relied upon combining conceptual thinking and existing data from previous experiments. This note describes the development of a simple correlation for pollution dispersion in urban areas.

Mathematical models often use the concept of a growing plume or puff, arising from different source types – the source being either continuous or instantaneous respectively. For releases of finite duration there are distinguishing criteria [6] for deducing the appropriate source type to model. Here we use the plume concept as the source-receptor distances planned for the field experiment (up to 500m), together with the proposed release duration (of 900s) and the design wind speed (of 2-5 m/s), should produce a plume-like result. A similar approach will later be developed using the puff concept in order to derive a similar simple model appropriate for instantaneous releases.

2. The theoretical basis of a simple correlation

The pollution dispersion in an urban topography can be thought of as a process ocurring over two regimes. A regime exists near to the source, where any buildings will be felt by the plume as very high obstacles; so high that the actual height may not affect the plume growth and thereby the pollutant dispersion. A second regime exists far from the source, where the plume height is much larger than the building height, and any buildings of the urban topography are most likely to be felt by the plume as a gross surface roughness.

For the second regime the dispersion process is well studied, and is often interpreted through the use of the surface roughness length and Monin-Obukhov similarity theory [1]. In this regime it has been noted that the maximum ground level concentrations reduce downwind from the source in a manner that can be expressed by

$$C \sim x^{-n} \quad \text{where n typically ranges from 1.5 to 1.75} \quad (1)$$

Such an approach will not be applicable for the near-source (possibly called the neighbourhood-scale regime). For this regime, an interesting deduction can be made based on dimensional analysis grounds. The pollutant concentration must be generally described by

$$CUH_r^2/Q = f(x/H_r) \qquad (2)$$

where C is the maximum concentration that would be measured at a ground-level receptor located on an arc a distance x from the source with a release rate Q subject to an advection wind speed U in an urban area with an average building height H_r.

If the actual building height cannot be felt by the plume when the building height is large compared to the plume height, then there can be no dependence on H_r in this limit. This directly leads to a general expression for the near-field pollutant concentration as being

$$CUH_r^2/Q = K(x/H_r)^{-2} \quad \text{or} \quad CU/Q = Kx^{-2} \qquad (3)$$

where K is a "constant". We anticipate that "constant" K will be a function of one or more non-dimensional parameters describing the urban topography e.g. λ_p, the dimensionless building plan area, and λ_f, the dimensionless building frontal area. But, for the present, we take K to be constant thoughout. In fact, we can expect that the dispersion will be maximised for some intermediate value of building packing density [], with very sparse obstacles or very densely packed obstacles both producing less dispersion than some intermediate packing density. The "constant" K may pass through a shallow minimum for typical urban topography.

Thus we have highlighted two regimes with surprisingly similar concentration reduction rates. It will be useful for urban dispersion studies, particularly those at neighbourhood scale that are near the limit of the two regimes, to report the plume-to-building height ratio (σ_z /H_r); the reason being that the ratio might be used to demarcate the near- from the far-field regimes. For example, a value of $\sigma_z /H_r =O(1) \approx 1$ (chosen here without any particular justification) could be used to distinguish the near-field ($\sigma_z /H_r < 1$) from the far-field ($\sigma_z /H_r > 1$). Additionally, and because the exponents for the two regimes are not greatly different, it is likely to be the case that extrapolation of either regime beyond the region of direct applicability may not lead to serious errors.

3. The empirical basis of the simple correlation

For a release rate Q (kg/s) at, or near ground level, an estimate of the maximum concentration C_{max} (kg/m^3) that would be measured at a ground-level receptor located on an arc a distance x (m) from the source, for a representative wind speed U (m/s), can be made based for example on a Gaussian Plume model [1]. It may not be clear at this stage what prescription of wind speed (U) would be appropriate to use to represent the plume growth in the urban topography, so we will just indicate what choice has been made for each example.

For such a plume, the Gaussian Plume model predicts:

$$C_{max}\, U/Q=2/(2\pi\sigma_y\sigma_z) \qquad (4).$$

Using measurements from field experiments, a simple correlation of the form given in equation (2), can be deduced. We quote three field experiments to deduce this empirical correlation: (i) the St Louis, (ii) the Salt Lake City, and (iii) the Birmingham City field experiments.

3.1 St Louis Experiments

The St Louis field campaign was conducted in the period between 1963-65 and consisted of 26 daytime and 16 evening experiments in seven series [9].One of the two tracer-release sites was located at ground level and the release duration was one hour. Tracer concentrations were monitored in three arcs of between _ and 10 miles.
Briggs [3] deduced from the field measurements in St Louis, the dispersion coefficients for these urban conditions, σ_y and σ_z as:

$$\sigma_y = 0.16x\,(1+0.0004x)^{-1/2} \qquad \text{and} \qquad \sigma_z= 0.14x\,(1+0.0003x)^{-1/2}$$

For these experiments $H_r \approx 25m$, and so we can deduce that $\sigma_z /H_r \approx 1$ when $x=175m$. At this downwind extent σ_y and σ_z can be approximated by the expressions: $\sigma_y \approx 0.16x$

and $\sigma_z \approx 0.14x$. Hence:

$$CU/Q = 7x^{-2}$$

It is not clear how the wind speed is characterised in Briggs [3] nor what averaging time is implied. However the above dispersion coefficients are commonly used with a wind speed measured at the source height, or averaged over the plume depth, or sometimes just that at 10m for lower sources. The averaging time is commonly taken to be 10 minutes.

3.2 Salt Lake City Experiments

The Salt Lake City (SLC) field campaign was conducted during October 2000 to investigate the urban nocturnal boundary layer (stable to neutral conditions) [5]. As part of this investigation meteorological and tracer experiments were conducted to study the vertical transport and mixing processes around a single downtown building, through the downtown area and the urban area. The SLC downtown area has buildings ranging in height from a few stories to 40 stories. The mean building height was estimated to be 16.4m [8]. For the downtown area domain, wind profile measurements were taken from the top of a 35-m-high building collecting wind data from 15m to 200m above the building top. Four tracers (SF6 and 3 PFT) were released. Integration times of tracer samplers ranged from 5min for SF6 to 4h for some PFT samplers. Only 30 minute average SF6 data are widely available and it is these that we have used below.

The SLC data sets were used for evaluation of a baseline dispersion model in [7]. A graph depicting the observed and predicted (with their baseline dispersion model) maximum concentrations as functions of distance from the source is adapted here and shown in Figure 1. Some 18 experiments were undertaken at night and with wind speeds (averaged from data at various locations in the city and at heights of 7,9,11,12,23 and 124m) ranging from 0.70 to 2.64 m/s. The data plotted are the average over all experiments together with the range of data. The concentrations are 30 minute averaged concentrations and this is quite large compared with the release duration of 60 minutes.

From this plot we can see that the mean concentration (normalised with the source release rates) arising from all the experiment has an exponent that is well approximated by –2 near to the source becoming closer to –1.5 further from the source, with a possible change around a downwind distance of 1000m. The ratio of this possible regime change to the average building height was 1000/16.4 or around 60; a value for which σ_z/H_r iwill be considerably larger than unity. We can fit the near-source data with

$$C/Q = 10\,x^{-2}$$

By introducing the average wind speed from all experiment of 1.37 m/s the correlation becomes

$$CU/Q = 13.7\,x^{-2}$$

Of course this result has involved much averaging and manipulation of the data. Some questions need to be asked and answered by looking at the data from individual experiments.

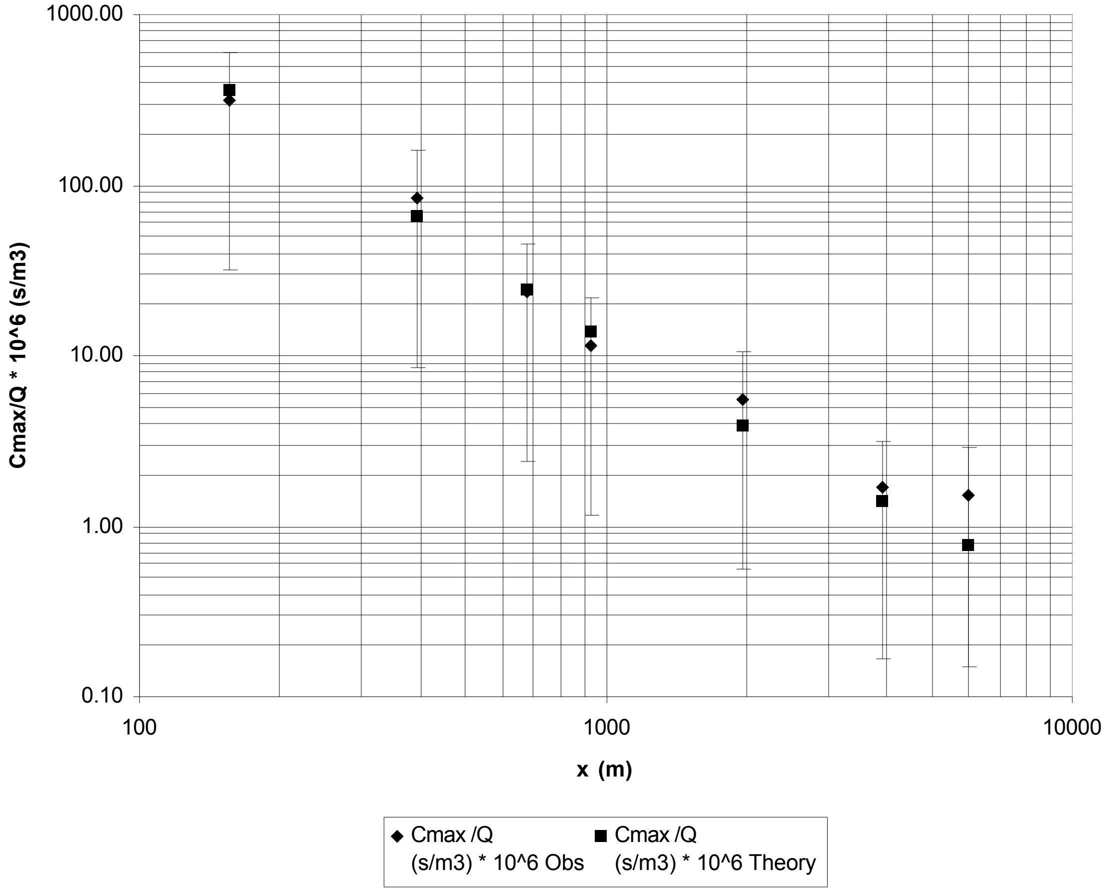

Figure 1: Salt Lake City Urban 2000 observed and predicted hourly-averaged C_{max}/Q for all 18 trials. The solid symbols represent the averages over all the trials, and the range of the 18 observations is shown as the vertical bar.

3.3 Birmingham City Experiments

The Birmingham City field campaign was conducted in the period of July 1999 to July 2000 to investigate the transport and dispersion of pollutants at neighbourhood scale[4]. The experiments used a finite duratrion release (15 and 20 minutes) of perfluoromethylcyclohexane (PMCH) and perfluoromethylcyclopentane (PMCP). The mean building height of the city centre was estimated to be around 25m. The release was made at a height of 4.5m and sampling sites ranged from 1km to 9 km from the source. The sample averaging times were 15, 3 and 6 minutes for 1st, 2nd and 3rd experiments respectively. The wind speed was approximately 4 m/s for all three experiments. This was the wind speed at 10 m height averaged over 10 meteorological stations set up for the PUMA campaign.

The first experiment did capture the plume well at a downwind distance of 3.5 km with a maximum concentration value of 2.16 μg/m^3. From this can be calculated that:

$$CU/Q \approx 26.5\, x^{-2}.$$

At 9km the only measurement gave

$$CU/Q \approx 8.1\, x^{-2}.$$

In the second experiment the plume was not well captured by the sensor array closer to the source and

$CU/Q \approx 0.05\, x^{-2}$. at x = 1 km while

$CU/Q \approx 12.9\, x^{-2}$. at x = 6.6 km.

In the third experiment

$CU/Q \approx 12\, x^{-2}$ at x = 1 km, while

$CU/Q \approx 6.5\, x^{-2}$ at x = 6.6 km.

From these very limited measurements in Birmingham we argue that

$$CU/Q \approx 10\text{-}20\ x^{-2}.$$

4. Summary

From these 3 field experiments we conclude that the near field maximum ground level concentrations might be usefully correlated with

$CUH_r^2/Q = K(x/H_r)^{-2}$ or $CU/Q = Kx^{-2}$ where K is in the range 10-20.

We anticipate that K will depend upon one or more dimensionless parameters that describe the urban topography. The difficulty in defining a useful and unambiguous wind speed in an urban context was apparent.

The form of correlation above is one in which the building height disappears. This unusual result can be argued for by noting that for buildings very high compared with the plume depth, the building height itself will not affect the dispersion process. The argument seems reasonable, however as the correlation appears to be applicable out to regions where σ_z/H_r is larger than unity there may be other explanations.

It was the above correlation that guided the design of the first DAPPLE tracer experiment. Wind tunnel results [10] supported this approach.

Though the correlation is presented in terms of the maximum concentration downwind of the source the result could be restated that the concentrations at any receptor a distance R from the source in any direction should be smaller than that provided by the correlation with R replacing x. This observation may be particularly useful for operational modelling.

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